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C.G. Carll

P. Wang

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Research
Note
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Data for Prediction of Mechanical Properties of Aspen Flakeboards

Charles G. Carll
and
Peiyuan Wang[2]

Introduction

Hot-pressed particleboards or flakeboards characteristically have a density gradient through their thickness. Because the mechanical properties of these boards increase substantially with an increase in density, a board with a density gradient through its thickness may be considered as a composite of layers having unequal mechanical properties. The effective bending properties of such a composite depend largely on the tensile/compressive properties of the outermost layers. Geimer et al. *(3)*[3] showed that bending stiffness of flakeboards could be predicted from layer tensile stiffness, and layer position and thickness using three-layer or multilayer analysis.

Design of particleboards or flakeboards with specific flexural properties by using three-layer or multilayer analysis requires knowledge of the tensile properties of the layers. Each layer may be considered as having an approximately uniform density through its thickness. Geimer *(2)* produced flakeboards which had uniform densities through their thickness in order to establish relationships between mechanical properties and the variables of specific gravity and flake alinement. Production of uniform-density boards was believed necessary as there was some indication that axial tensile and compressive properties parallel to the board surface were influenced by density distribution through the board thickness. The prediction equations developed by Geimer for tensile stiffness of uniform-density boards were found usable and moderately accurate for use in the multilayer prediction equation for bending stiffness mentioned previously.

Geimer produced uniform-density flakeboards of Douglas-fir and oak via a method involving pressing the flake mat to final target thickness between initially cold platens and subsequently heating them. This method involved exertion of very high pressures on a cold mat and, consequently, possible flake damage by crushing. Geimer has since developed a method of pressing particleboard or flakeboard mats which involves injection of steam into the mat. This method results in boards of uniform density through their thickness and may not involve exertion of high pressure on the mat. It was suspected, however, that injection of steam might result in inferior interflake bonding due to excessive resin absorption by flakes (when resin viscosity is lowered by the presence of steam), or due to transport of resin to mat edges by the steam, or due to unidentified phenomena.

The purpose of this research was to compare the relative strength and stiffness properties of uniform-density aspen flakeboards produced by the two pressing methods.

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[1] Maintained at Madison, Wis., in cooperation with the University of Wisconsin.

[2] The authors are respectively; Technologist, Structural Composite Products, U.S. Forest Products Laboratory, and Deputy Director, Department of Particleboard, Institute of Wood Industry, Chinese Academy of Forestry, Beijing. This study was performed while Mr. Wang was a visiting scientist at the U.S. Forest Products Lab.

[3] Italicized numbers in parentheses refer to literature cited at end of report.

Experimental Design and Procedure

Homogeneous boards 0.5 by 24 by 28 inches (13 by 610 by 711 mm) were constructed of disk-cut aspen flakes, 0.020 by 2.25 inches (0.51 by 57.22 mm) by random width. Triplicate boards were made at each of four target density levels (30, 40, 50, and 60 lb/ft^3) (481, 641, 801, and 961 kg/m^3) for both cold-pressing and steam-injection pressing methods. Flake alinement was not attempted in any of the boards. All boards contained 5 percent phenolic resin and 1 percent wax based on wood ovendry mass. Moisture content of the mats prior to pressing was 9 percent, based on total ovendry mass.

Cold pressing was performed as previously described by Geimer *(2)*. The mat of flakes was closed to stops between cold press platens. Then the platens were heated, and after sufficient heating had occurred, the board was cooled in the press. Heat input to the mat via contact with the platens could be controlled by throttling the steam flow to them. This permitted the press operator to hold the core temperature of the pressed mat at a constant level. Core temperature of these boards was raised to 230° F (110° C) and held constant for 8 minutes, subsequent to which the board was cooled in the press until its centerline temperature fell to 180° F (82° C). The platens of the press used to manufacture these boards had passageways through which water could pass to cool the press quickly.

The main platens of the press used for producing the steam-injected boards were heated by circulating oil. These were heated to 325° F (163° C). Accessory platens with internal passageways and perforated faces were attached to the oil-heated platens. These perforated-face platens were used to inject saturated steam at 210 lb/in^2 (1.45 MPa) gauge pressure and 98 percent quality into the mat of flakes. Neither the oil-heated press platens nor the steam-injection platens attached to them had a water jacket; therefore the press could not be cooled quickly, as could the press used to manufacture cold-pressed boards. This initially was not perceived as a problem since prior work indicated that injection of steam into a mat kept interparticle passageways open. It was therefore believed that boards into which steam had been injected would breathe, and that cooling in the press would not be necessary to avoid explosive delamination (blowing) of these boards.

Steam was injected while closing the mat of flakes to target thickness. The board was kept in the press for 8 to 9 minutes after the board centerline temperature first reached 212° F (100° C). No press stops were used, and pressure exerted on the mat was automatically adjusted to keep the board at approximate target thickness.

Long periods of steam injection were suspected to result in starved glue joints between flakes. For this reason steaming times were kept to approximately the minimum that would raise core temperature to at least 212° F. Periods of steam injection were 6 seconds for boards of 30, 40, and 50 lb/ft^3 target density, and 9 seconds for boards of 60 lb/ft^3 target density. Prior work had shown that mat density at which steam was injected was critical— if injected too soon (at too low a density) flakes might be "blown out" of the press, and if the mat were pressed too far before injection of steam (i.e. packed too tightly) steam could not be forced into the mat. For this work, steam injection was started at 15 lb/ft^3 (240 kg/m^3) mat density. Steam injection was continued until the mat was pressed to target thickness, for boards of 30 and 40 lb/ft^3 target density. Steam injection was discontinued before the mat reached target thickness for boards of 50 and 60 lb/ft^3 target density. In these boards, steam injection was stopped before closing to target thickness because: (a) it was desired to keep steam injection times short, (b) it was believed necessary, as mentioned above, to inject steam starting at about 15 lb/ft^3 density, and (c) a closing speed required to compress the mat from 15 to 50 lb/ft^3 in 6 seconds, or 60 lb/ft^3 in 9 seconds would have resulted in exertion of greater pressures on the mat. Table 1 shows the maximum pressures exerted on the mats for the different pressing methods and target densities.

Table 1.—Maximum pressures exerted on mats for different pressing methods and target densities

Pressing method	Target density	Mat pressure
	Lb/ft^3	Lb/in.^{2}
Cold	30	858
	40	985
	50	1,399
	60	1,502
Steam	30	136
	40	194
	50	503
	60	795

Board Testing

In prior work by Geimer, flakeboards of 60 lb/ft^3 produced by cold pressing had a slight density gradient which could be mostly eliminated by sanding. Since sanding might affect failure mechanisms in mechanical testing, all boards were sanded to remove about 0.025 inch (0.64 mm) from each face. Subsequent to sanding, specimens were cut from each board for bending, compression and tension (parallel to the board surface), internal bond tests, and for density gradient measurement. Density gradients were measured using a planer to remove layers 0.030 inch (0.762 mm) thick from ovendried specimens. Mechanical test specimens were conditioned to equilibrium at 74° F (23° C) and 65 percent relative humidity (RH) prior to testing, in accordance with American Society for Testing and Materials (ASTM) standard method D 1037-72a *(1)*.

Results and Discussion

Board Pressing

For steam-injected boards of 30 and 40 lb/ft^3 density, the board core temperatures were between 230° F (110° C) and 242° F (117° C) 8 minutes after the injected steam brought the core to 212° F. This indicated that either all moisture had been driven out of the boards, or that the boards were acting as pressure vessels, and the steam-injection process did not do a perfect job of keeping interparticle passageways open. Despite the fact that core temperatures of these boards exceeded 212° F, the press could be opened without explosive delamination occurring.

Core temperatures would rise to over 270° F (132° C) for steam-injected boards of 50 and 60 lb/ft^3 density. These boards would explosively delaminate unless cooled in the press. Explosive delamination (blowing) indicated that these boards were acting as pressure vessels, and hence that the steam-injection process did not keep interparticle passageways sufficiently open.

Specific Gravity

Considerable variation in specific gravity (SG) was found within individual boards, and between boards of the same target density and pressing method. There was some overlap of SG between the steam-injected boards with target densities of 50 and 60 lb/ft^3. Mean SG's, and within-board, and between-board variances in SG's of the different mechanical test specimens are shown in table 2. Variance values are included in table 2 merely to illustrate what is meant by the statement that "considerable" variation in SG was found within and between boards; the variance values are of poor accuracy because sample size was small. The 1-inch by 4-inch (2.54-cm by 10.2-cm) compression test specimens showed greatest within-board variation in SG. This was probably due in part to the small size of these test specimens, and in part to the fact that two of the four compression test specimens from each board were from near the board edge, while the other two were from near the board center. Considering all test specimen types, within-board variation in SG was higher for cold-pressed than for steam-injected boards, but between-board variation was higher for steam-injected boards.

Table 2.—Mean specific gravity level, mean within-board variance in specific gravity, and between-board variance in specific gravity for combinations of pressing method and target density

Pressing method	Target density	Mean specific gravity of specimen type			
		Internal bond	Tension	Compression	Bending
	Lb/ft³				
Cold	30	0.557	0.574	0.565	0.560
Cold	40	.723	.725	.717	.741
Cold	50	.885	.884	.885	.950
Cold	60	1.066	1.067	1.040	1.105
Steam	30	.549	.562	.559	.564
Steam	40	.710	.734	.728	.735
Steam	50	.948	.943	.945	.930
Steam	60	1.027	1.028	.986	1.040
		Mean within-board variance in specific gravity of specimen type			
Cold	30	0.00034	0.00090	0.00064	0.00020
Cold	40	.00042	.00094	.00242	.00025
Cold	50	.00098	.00089	.00843	.00125
Cold	60	.00084	.00133	.01118	.00094
Steam	30	.00035	.00166	.00035	.00110
Steam	40	.00154	.00043	.00137	.00066
Steam	50	.00054	.00179	.00115	.00063
Steam	60	.00107	.00044	.00549	.00022
		Between-board variance in specific gravity of specimen type			
Cold	30	0.00010	0.00015	0.0003	0.00009
Cold	40	.00075	.00008	.00113	.00037
Cold	50	.00008	.00027	.00037	.00014
Cold	60	.00018	.00021	.00061	.00002
Steam	30	.00014	.00011	.00066	.00031
Steam	40	.00008	.00049	.00072	.00018
Steam	50	.00259	.00098	.00149	.00086
Steam	60	.00010	.00005	.00073	.00026

Density Profile

Examination of density profile data showed some consistent but slight density profiles, and some nondescript variation in density with position through the board. Where there was consistent and identifiable density distribution, density at the board centerline was from 2 to 8 percent less than board average density, with density increasing to a peak either at the board surface or somewhere between the centerline and the surface. The most striking density distributions were shown by boards of 60 lb/ft³ nominal density produced by injecting steam into the mat. These boards showed a centerline density 8 percent below board average density; other boards showed a centerline density of from 2 to 5 percent below board average density. Perhaps the density distribution in 60 lb/ft³ steam-injected boards was induced by the pressing procedure in which there was a 10-second period between the time steam injection ended and the mat reached target thickness.

Variability in Mechanical Properties

Variability in mechanical properties tended to increase with increasing SG, particularly for steam-injected boards. Geimer *(2)* reported increasing variance in compression, tension, and bending properties of cold-pressed uniform-density boards with increasing SG and alinement. In order to account for this changing variability, he used prediction models involving natural logarithmic transformations. In this study conducted by Carll and Wang, flake alinement was not included as a factor. Straight-line regression models of mechanical properties versus SG are presented (figures 1-4). These regression coefficients are unbiased, but their variance estimates may be misleading (so are not reported).

In all types of mechanical tests there were some observations which appeared to be outliers. For this reason we cannot make exact quantitative statements regarding differences in variability between pressing methods, or regarding statistical equivalence of regression equations.

Internal Bond

Plots of linear regression equations of internal bond (IB) versus SG for the two pressing methods are shown in figure 1. Slopes of the regression lines appear to be statistically equivalent, but over the range of SG examined in this study, steam-injected boards appear to have slightly higher IB strengths than cold-pressed boards of equivalent density.

It is believed that the greater IB strength of steam-injected boards may be the result of greater plasticization of flakes by this pressing method, and subsequently less fracture of wood cell walls in the flakes by crushing. Fracture of wood cell walls would reduce their strength in tension perpendicular to the grain, and could thereby result in lower IB strengths. Examination of failed IB specimens indicated that cold-pressed boards, particularly those of higher density, had a slightly greater tendency to show IB failure within flakes (as opposed to bond failure between flakes) than did steam-injected boards of similar density. The degree of difference in mode of IB failure exhibited by the different board types was not striking, however.

Tensile Properties

Despite the fact that steam-injected boards appear to have higher IB strengths than cold-pressed boards of equivalent density, they did not show consistently higher values in tension, compression, or bending properties than did cold-pressed boards. A possible explanation for this is that IB strength may be more negatively affected by cell wall fracture due to crushing than are tension, compression, or bending properties.

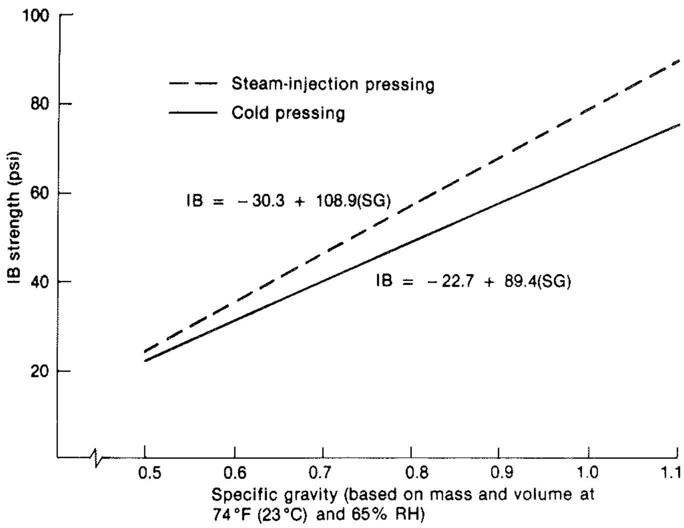

Figure 1.—Regression equation plots of internal bond strength versus specific gravity for cold pressing, and steam-injection pressing. (ML835275)

Plots of linear regression equations for tensile properties are shown in figure 2. The regression equations of tensile stress versus SG are similar, both in slope and intercept. Equivalency cannot be rejected although it appears that cold-pressed boards may have greater tensile strength, particularly at low SG levels. The regression equations of tensile modulus of elasticity (MOE) versus SG do not have parallel slopes, with the steam-injected boards showing greater increase in tensile MOE with increasing SG.

Comparative behavior between pressing methods of tensile strength and tensile MOE may reflect differences in cell wall fracture by crushing. In cold-pressed boards (in which it is suspected that cell wall fracture may occur) more fracture is expected at higher board densities than at low board densities. Consequently, cold-pressed boards may show superior tensile strength to steam-injected boards at low SG levels where the comparative advantage of steam-injection pressing (i.e. reduced flake damage) is small (or at least less than at higher SG levels). Likewise, increases in tensile MOE with increasing SG may not be as great for a pressing method in which cell wall fracture becomes comparatively greater with increasing SG. These arguments should be considered only as hypotheses, since the effect of flake damage on tensile properties of these boards has not been demonstrated.

The behaviors of tensile strength and tensile MOE were not exactly alike. The probable reason for nonidentical behavior has to do with variability in specimens of large-flake flakeboard. For determination of tensile MOE elongation was measured over a 2-inch (5.08-cm) distance, which was the necked-down section of the test specimen, but tensile failure often did not occur within this necked-down section. When tensile failure did not occur in the necked-down section, calculation of cross-sectional area at the point of failure could only be roughly approximated. For this reason, even when tensile failure did not occur completely within the necked-down section of the test specimen, maximum tensile stress was calculated as though it had. The result was that, in these cases, the calculated value of tensile strength was higher than that of the specimen as a whole, but lower than that of the necked-down section of the specimen (which was supposed to have failed).

In order to overcome problems associated with test variability, which occur when small test specimens are used to determine mechanical properties, it appears that for large-flake flakeboards such as those manufactured in this study, the necked-down portion of tensile test specimens should be lengthened beyond 2 inches, and elongation of these tensile test specimens should be measured over a distance greater than 2 inches.

Compressive Properties

Plots of linear regression equations for compressive properties are shown in figure 3. The regression equations of compressive strength versus SG may be equivalent, both in slope and elevation. Over the SG range investigated in this study, cold-pressed boards appear to have slightly higher compressive strength values than steam-injected boards of equivalent density, but the small difference is not of practical significance. The regression equations of compressive MOE versus SG may also be equivalent in slope and intercept. The regression plots suggest that cold-pressed boards may show superior compressive MOE to steam-injected boards at lower board densities.

Bending Properties

Plots of linear regression equations for bending properties are shown in figure 4. The regression equations of bending MOR versus SG may be equivalent, both in slope and intercept, although cold-pressed boards may be slightly stronger at low SG levels. Such behavior parallels that of tensile strength, upon which bending strength of flakeboards depends to a considerable degree. Behavior of bending MOE differed for the two pressing methods. The regression of bending MOE versus SG is much steeper for steam-injected boards than for cold-pressed boards and the regression lines for the two methods cross within the range of SG examined in this study. This may reflect on cell wall fracture which may occur when cold pressing to high densities. It probably also reflects on the slight but consistent density gradients exhibited by steam-injected boards of 60 lb/ft^3 target density.

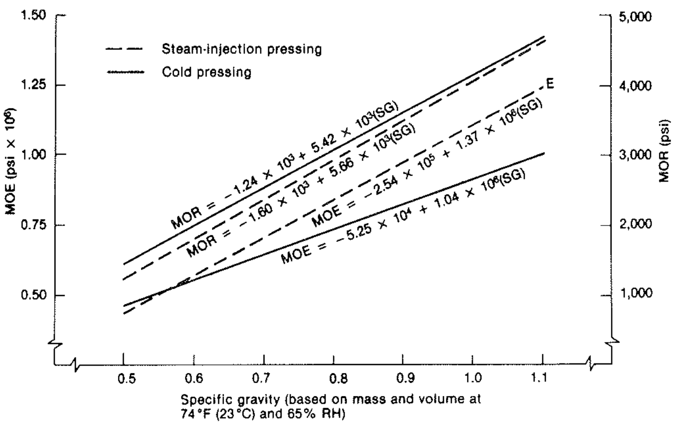

Figure 2.—Regression equation plots of tensile properties versus specific gravity for cold pressing, and steam-injection pressing. (ML835276)

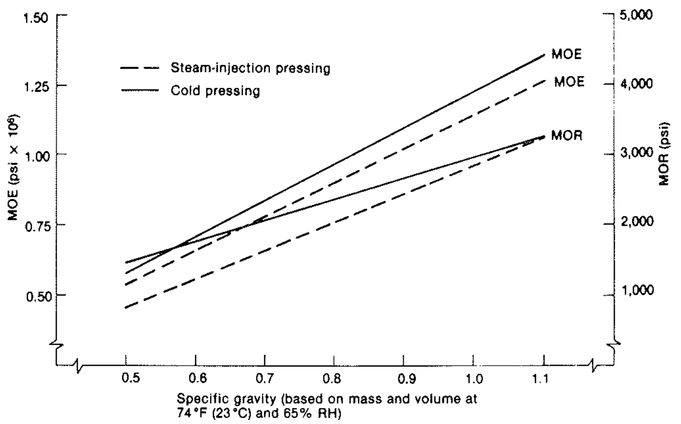

Figure 3.—Regression equation plots of compression properties versus specific gravity for cold pressing, and steam-injection pressing. (ML835277)

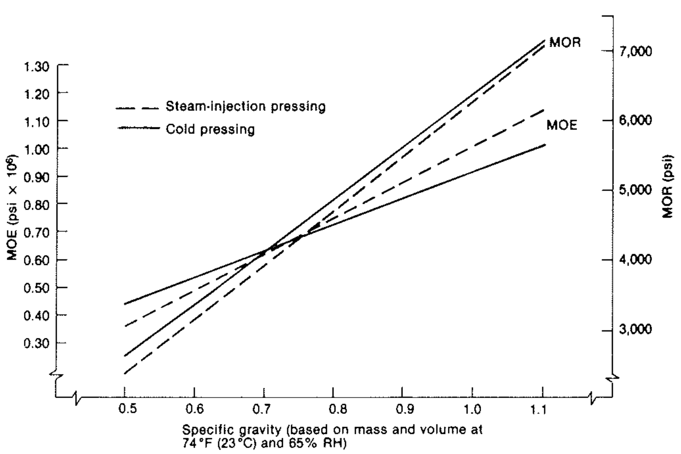

Figure 4.—Regression equation plots of bending properties versus specific gravity for cold pressing, and steam-injection pressing. (ML835278)

Prediction of Effective Bending MOE's of Gradient-Density Boards

In order to test the worth of the regression equations of tensile stiffness versus SG for prediction of "effective" bending MOE of gradient-density boards, eight normally pressed, gradient-density boards were manufactured, tested in bending, and measured for density distribution. Measurement of layer densities (or specific gravities) yielded values which were inserted into equations of tensile MOE versus SG. The resulting predicted layer tensile MOE values were then used to calculate "effective" bending MOE by the method presented by Geimer et al. *(3)*. Predicted "effective" bending MOE values were then compared with measured bending MOE values (table 3). At a target density of 35 lb/ft^3 (561 kg/m^3), use of the regression equation for cold-pressed boards yielded slightly higher values of predicted "effective" bending MOE than did use of the regression equation for steam-injected boards; at target densities of 45 and 55 lb/ft^3 (721 and 881 kg/m^3) the opposite was true. This reflects the behavior of tensile MOE of uniform-density boards (i.e. that steam-injected boards show a greater rate of increase in tensile MOE with increasing SG).

Unfortunately, direct comparison of predicted "effective" bending values with measured values was not possible due to an error in experimental procedure. Density profile measurements were made on specimens in the ovendry condition, while regression equations of tensile MOE versus SG of uniform-density boards were based on SG values where SG was calculated on the basis of mass and volume at equilibrium conditions of 65 percent RH at 74° F. The result was that layer SG values obtained from gradient-density boards were too low for insertion into regression equations of tensile MOE versus SG obtained from uniform-density boards. When the equation of tensile MOE versus SG for cold-pressed boards was used to calculate layer MOE values, the predicted "effective" bending values were from 7 to 25 percent lower than measured values. When the equation for steam-injected boards was used to calculate layer MOE values, the predicted "effective" bending values were from 12 to 18 percent lower than measured values. Larger prediction errors were found for gradient-density boards of 55 lb/ft^3 nominal density than for gradient-density boards of lower average density. The 55 lb/ft^3 gradient-density boards had surface-layer SG's approximately equal to or exceeding SG's of the densest of the specimens from the uniform-density boards. For the eight gradient-density boards examined, calculated correlation coefficients between mean measured bending MOE and predicted "effective" bending MOE were 0.992 and 0.995, respectively, when equations for cold-pressed and steam-injected uniform-density boards were used to predict layer tensile MOE's.

Table 3.—Measured and predicted bending modulus of elasticity values for gradient-density boards

Board	Target density	Mean measured bending modulus of elasticity[1]	Predicted bending modulus of elasticity using regression for cold-pressed boards[2]	Predicted bending modulus of elasticity using regression for steam-injected boards[3]
	Lb/ft^3		Lb/in.^{2} $\times$ 10^3	
A	35	604	562	523
B	35	653	593	565
C	35	604	558	516
D	45	845	683	689
E	45	879	736	759
F	45	855	729	749
G	55	1,135	874	945
H	55	1,109	834	904

[1] Mean of four measurements per board.

[2] Predicted from layer SG's using regression of tensile MOE versus SG for cold-pressed uniform-density boards to calculate tensile MOE of board layers.

[3] Predicted from layer SG's using regression of tensile MOE versus SG for steam-injected uniform-density boards to calculate tensile MOE of board layers.

Conclusions

(1) Steam-injected aspen flakeboards of the type manufactured in this study did not "breathe" at board density levels of 50 and 60 lb/ft^3 but acted as pressure vessels and would explosively delaminate unless cooled in the press.

(2) Variability in mechanical properties of nonalined uniform-density boards appeared to increase with increasing board SG, particularly for steam-injected boards.

(3) Steam-injection pressed boards appeared to have slightly higher IB strengths than cold-pressed boards of equivalent density. The lower IB strength of cold-pressed boards may be due to fracture of wood cell walls by crushing which occurs when high pressures are exerted on a mat of nonplasticized flakes. Fracture of the cell walls may reduce the strength of the flakes in tension perpendicular to the grain. It is believed that less cell wall fracture occurs when steam injection of mats is practiced.

(4) Despite the fact that steam-injected boards generally had higher IB strengths than cold-pressed boards of equivalent density, they did not show consistently higher values in tension, compression, or bending properties than did cold-pressed boards.

Perhaps mitigation of fracture of wood cell walls (referred to above) does not affect mechanical properties of flakes as they may be stressed in tension, compression, or bending tests of flakeboard specimens. Alternatively, adhesive bond between flakes may be the controlling factor in these tests, and hence, reduction in flake damage may not be reflected in these mechanical properties of flakeboards.

(5) Steam-injected boards showed greater rates of increase in tensile MOE and bending MOE with increasing SG than did cold-pressed boards. Furthermore, at lower density cold-pressed boards appeared to have superior tensile strength, compressive MOE, and bending strength than steam-injected boards. This suggests that cell wall fracture may occur when cold-pressing to high densities, and this cell wall fracture may affect mechanical properties other than IB strength.

(6) Alteration of the standard tension test specimen (as prescribed by American Society for Testing and Materials (ASTM) Standard Method D 1037) appears desirable when testing flakeboard specimens made of disk-cut flakes 2.25 inches or longer.

(7) Either cold pressing or steam-injection pressing can be used to produce uniform-density boards to obtain tensile MOE values used to predict "effective" bending stiffness of gradient-density boards.

Limitations and Shortcomings

The press used in this study for producing steam-injected boards did not permit quick cooling of boards in the press. Since steam-injected boards of 50 and 60 lb/ft^3 target density did not "breathe" and had to be cooled in the press, total press times for these boards was from 21 to 25 minutes. Such long press times, with peak core temperatures reaching over 270° F may have resulted in a weakening of resin-wood bonds. If it were possible to quickly cool these boards in the press and/or keep core temperatures from exceeding approximately 230° F (as was done for cold-pressed boards), the steam-injected boards of 50 and 60 lb/ft^3 density may have shown much superior mechanical properties than those produced for this study, and therefore may have shown much superior mechanical properties than cold-pressed boards of equivalent density. It is, therefore, plausible that high-pressure press closing may have greater negative effect on mechanical properties of flakeboards than this study would indicate.

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